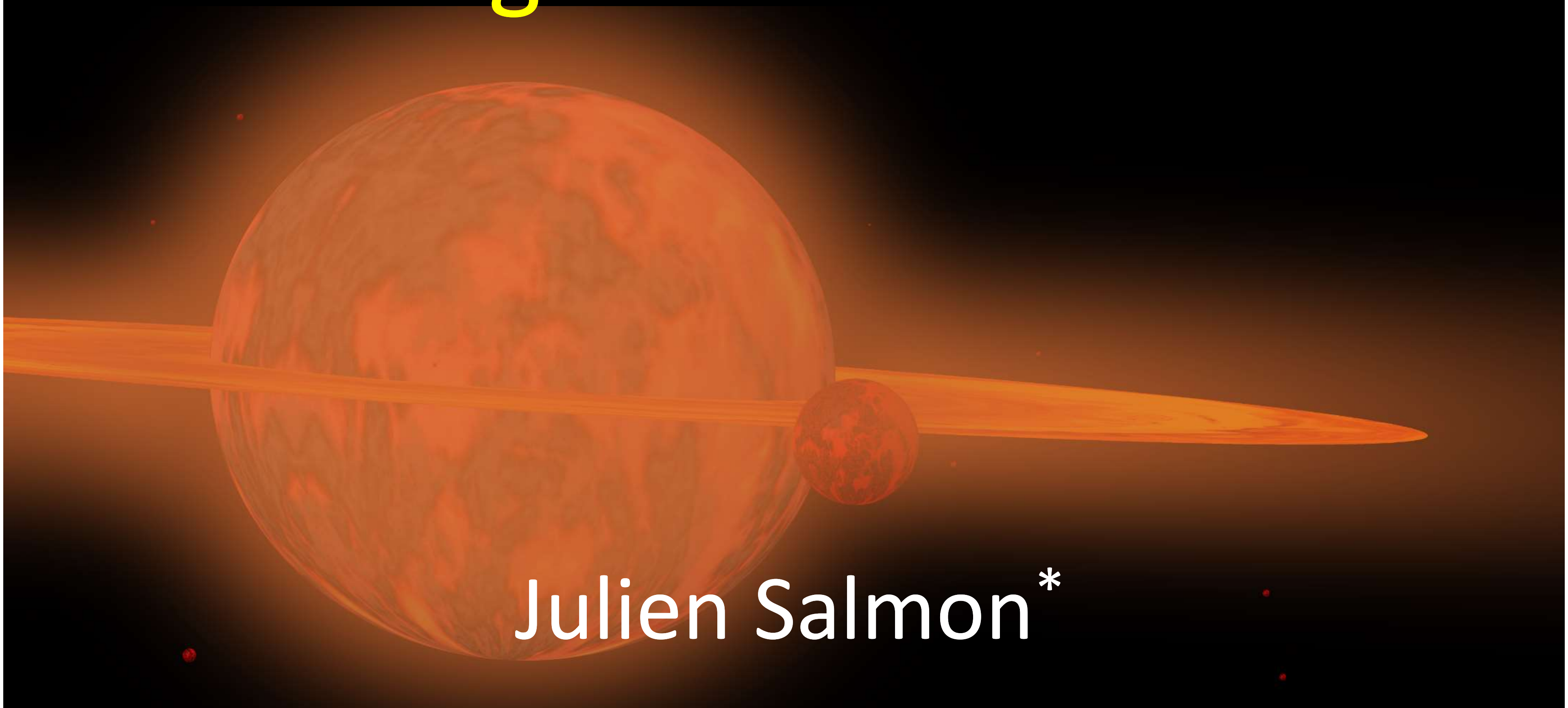
Origin of the Moon



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A unique body

Mercury: no satellite

Venus: no satellite

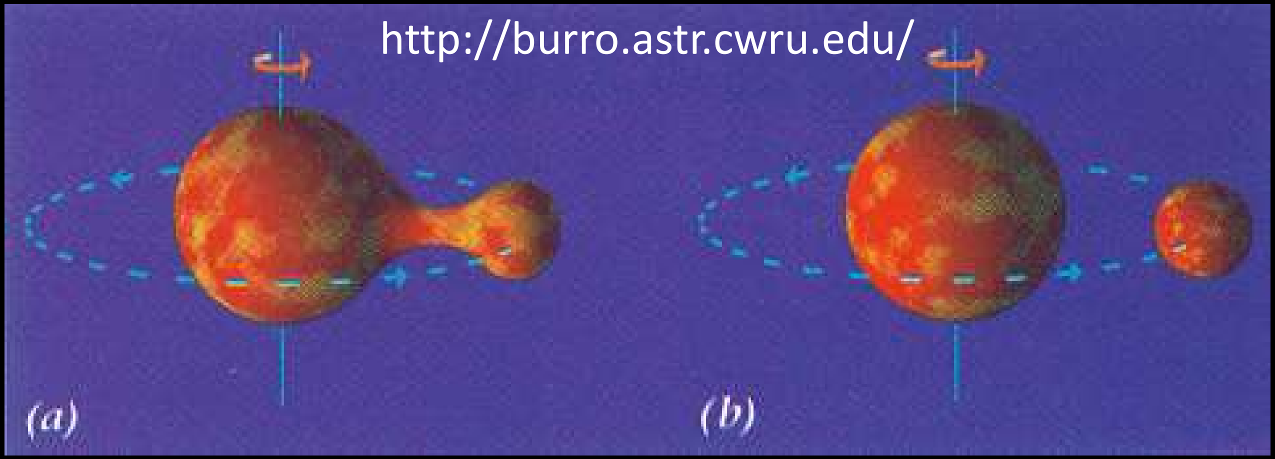
Earth: 1 large satellite

Mars: 2 small satellites

- The Moon is the only large satellite of the terrestrial planets
  - Its mass is ~1% of the mass of the Earth
  - Phobos & Deimos are ~10^{-8} of the mass of Mars
- The Moon's density is $3.3 g/cm^3$, indicating a small iron core
- The Moon currently orbits at ~$60R_E$. It was initially much closer and moved away due to tidal interaction with the Earth

Theories of Moon origin: Fission

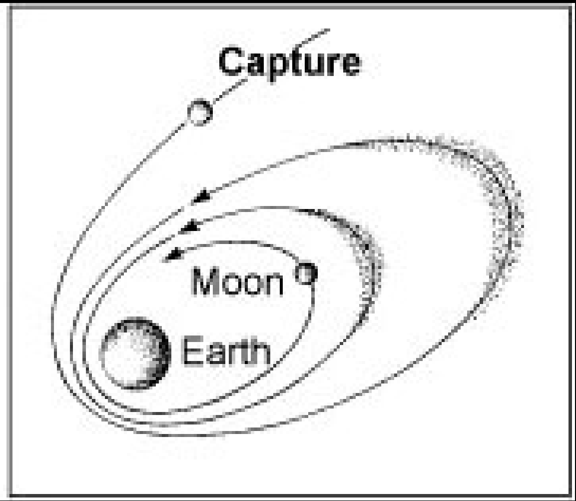
- Idea: Earth rotates so fast that material is ejected



- Problems:
  - How do you create such a state?
  - Earth-Moon angular momentum too low

Theories of Moon origin: Capture

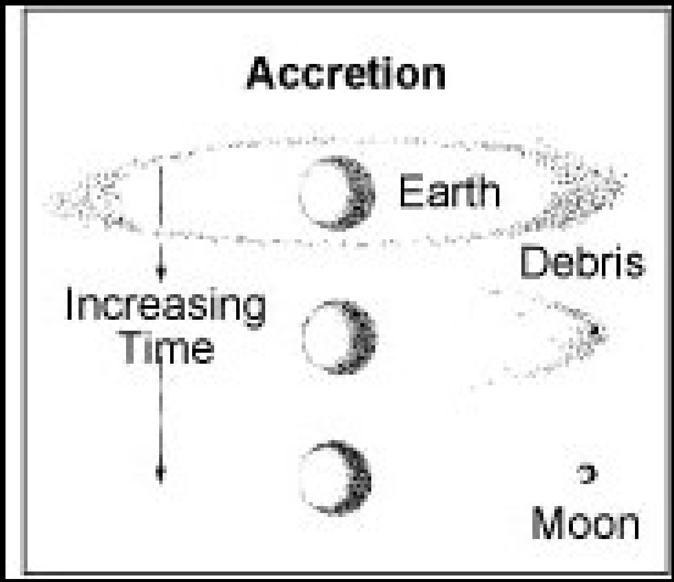
- Idea: Moon is a wandering object that passed close to the Earth and was captured



- Problems:
  - Encounter velocity is high, need to dissipate kinetic energy
  - Not achievable by tidal dissipation
  - Gas drag: need low encounter velocity and dissipation of gas to avoid inward drift of the Moon

Theories of Moon origin: Co-accretion

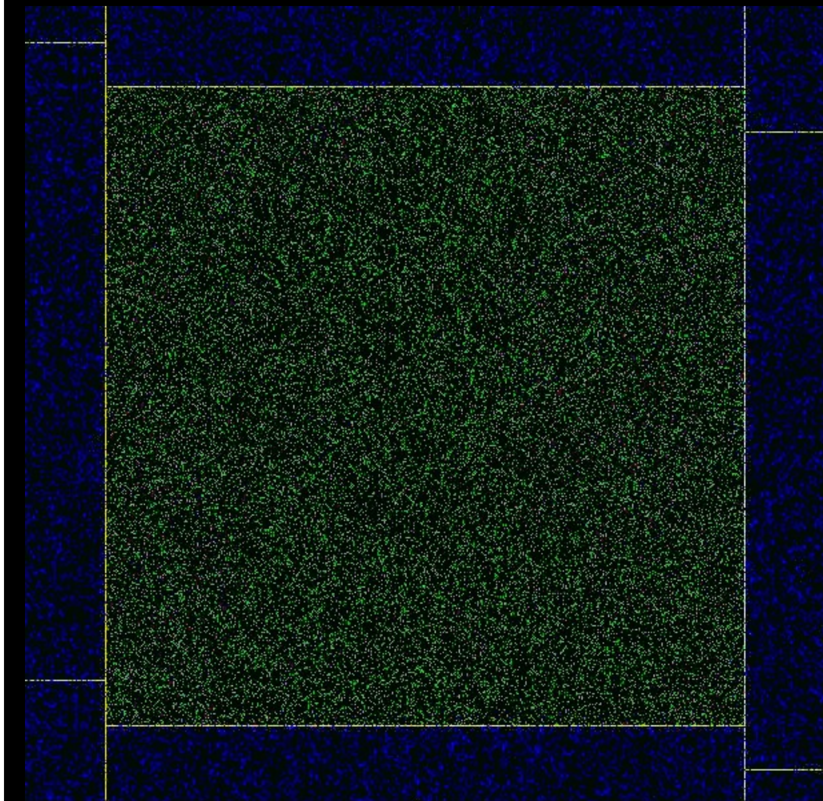
- Idea: planetesimals collide inside Earth's Hill sphere, debris form a disk from which Moon accreted

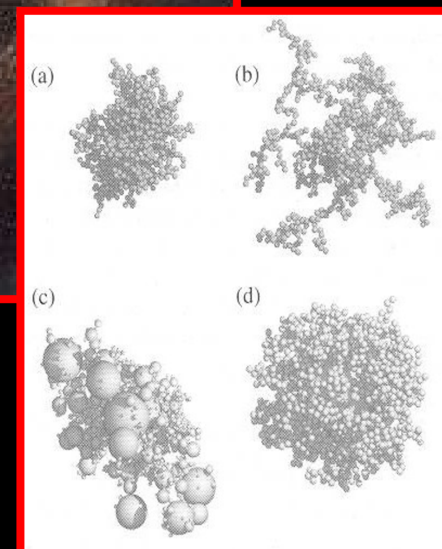


- Problem:
  – How do you explain low-iron content of Moon?

Insights from planet formation

Animation from Tanga et al. (2003)





- Gravity causes dust to collect into larger planetesimals (asteroid- or comet-like bodies).
- Planetesimals collide and form larger bodies. Over time, they grow into Moon/Mars-sized protoplanets.

Giant Impact theory

Impact of a ~Mars-size object on proto-Earth ejects material onto orbit from which the Moon accreted

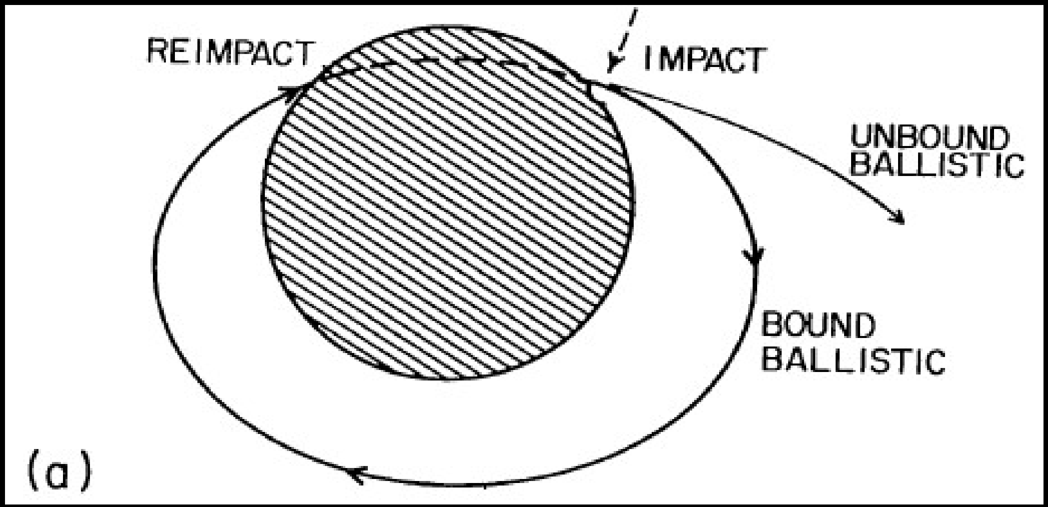
CONSTRAINTS:

1) Current angular momentum of Earth-Moon system
   - *AM roughly conserved over 4.5 Gyr (< 10% loss due to solar tides)*
   - *Moon slowed down Earth by tides as it moved away*
   - *Implies initial Earth day ~5 hrs when Moon formed close to Earth*

2) Need to put enough mass in orbit to produce a Moon

3) Low lunar density → lunar iron fraction < 0.1

Mechanism of orbital injection?



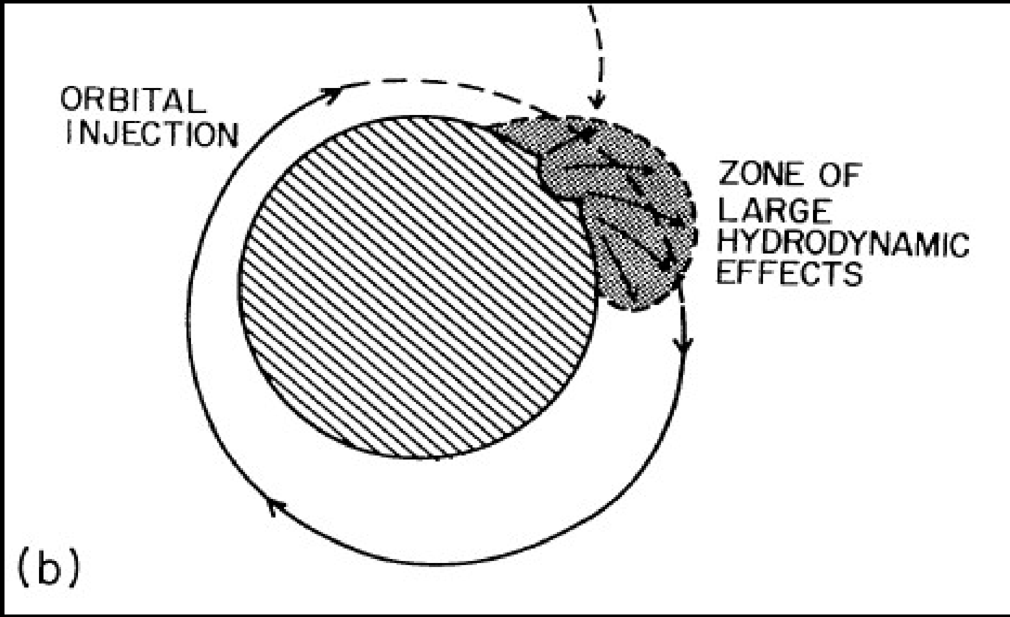
Upon impact, debris receive a positive acceleration

Follows the negative acceleration from Earth's gravity

Total energy of the debris:

- $> 0 \Rightarrow$ escapes on hyberbolic orbit
- $< 0 \Rightarrow$ traverses a close elliptical orbit that eventually reimpacts Earth

Mechanism of orbital injection?

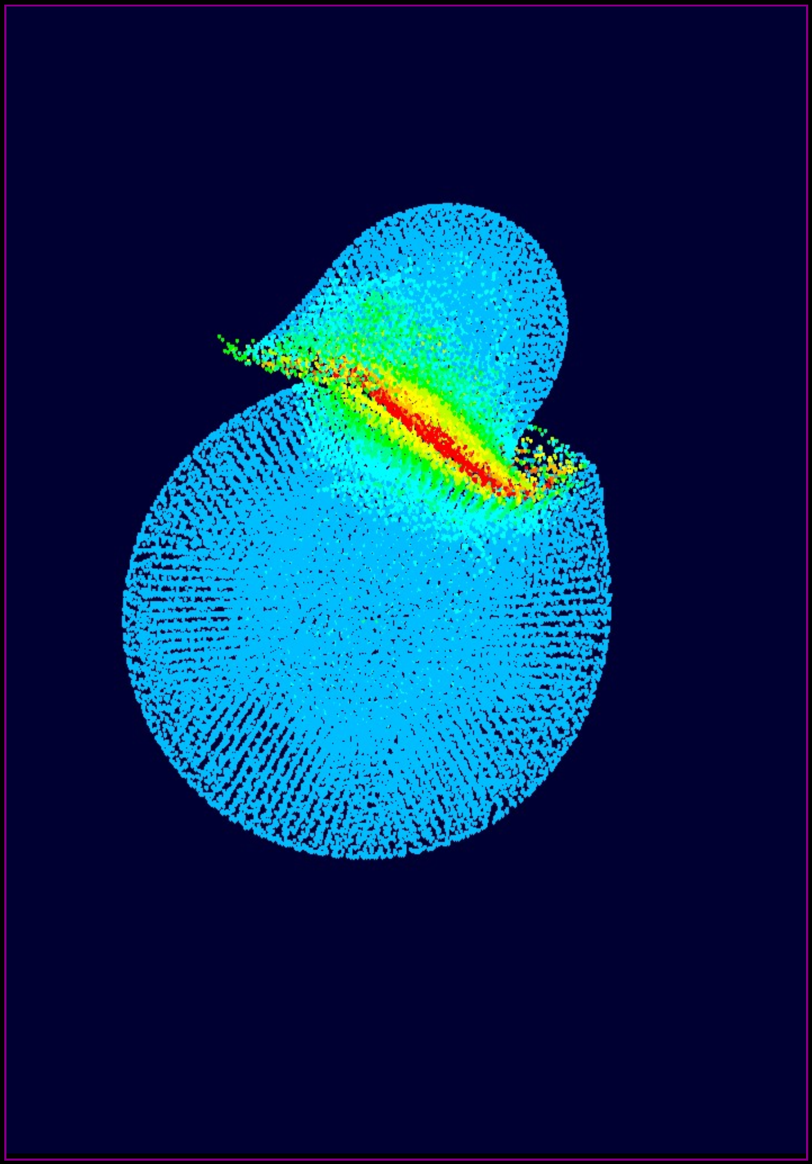


BUT…

Effects such as pressure gradients increase energy and angular momentum of the material $\Rightarrow$ lift periapse above surface

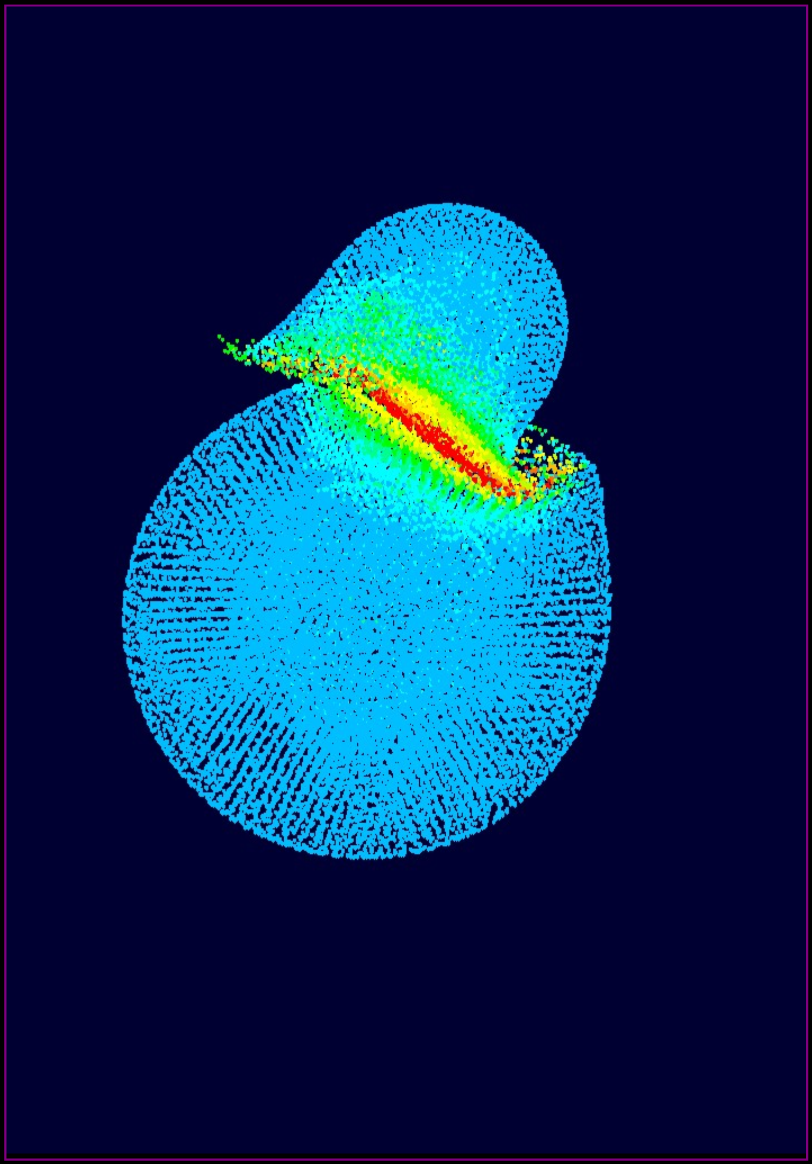
Modeling giant impacts: Approach

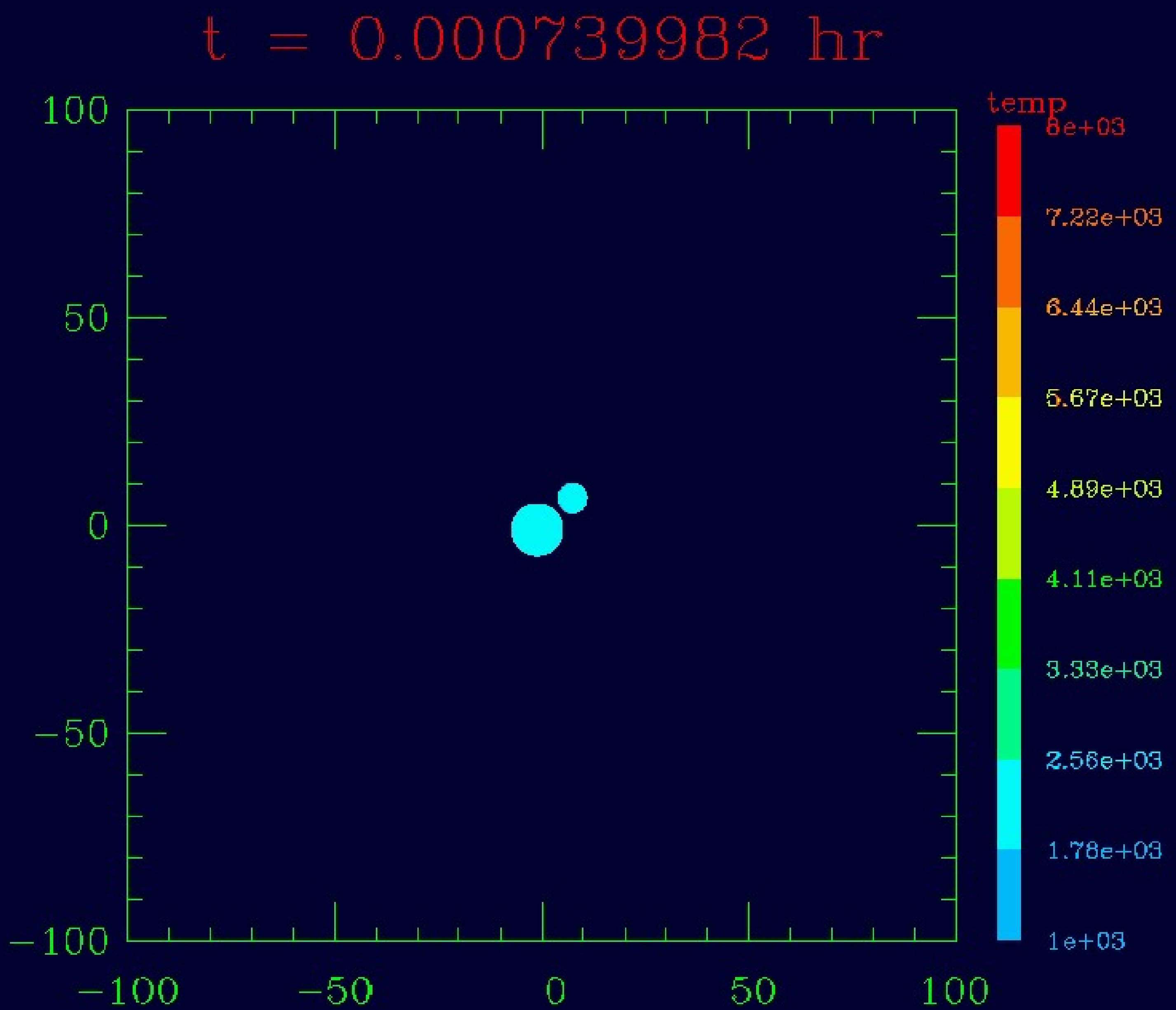
→



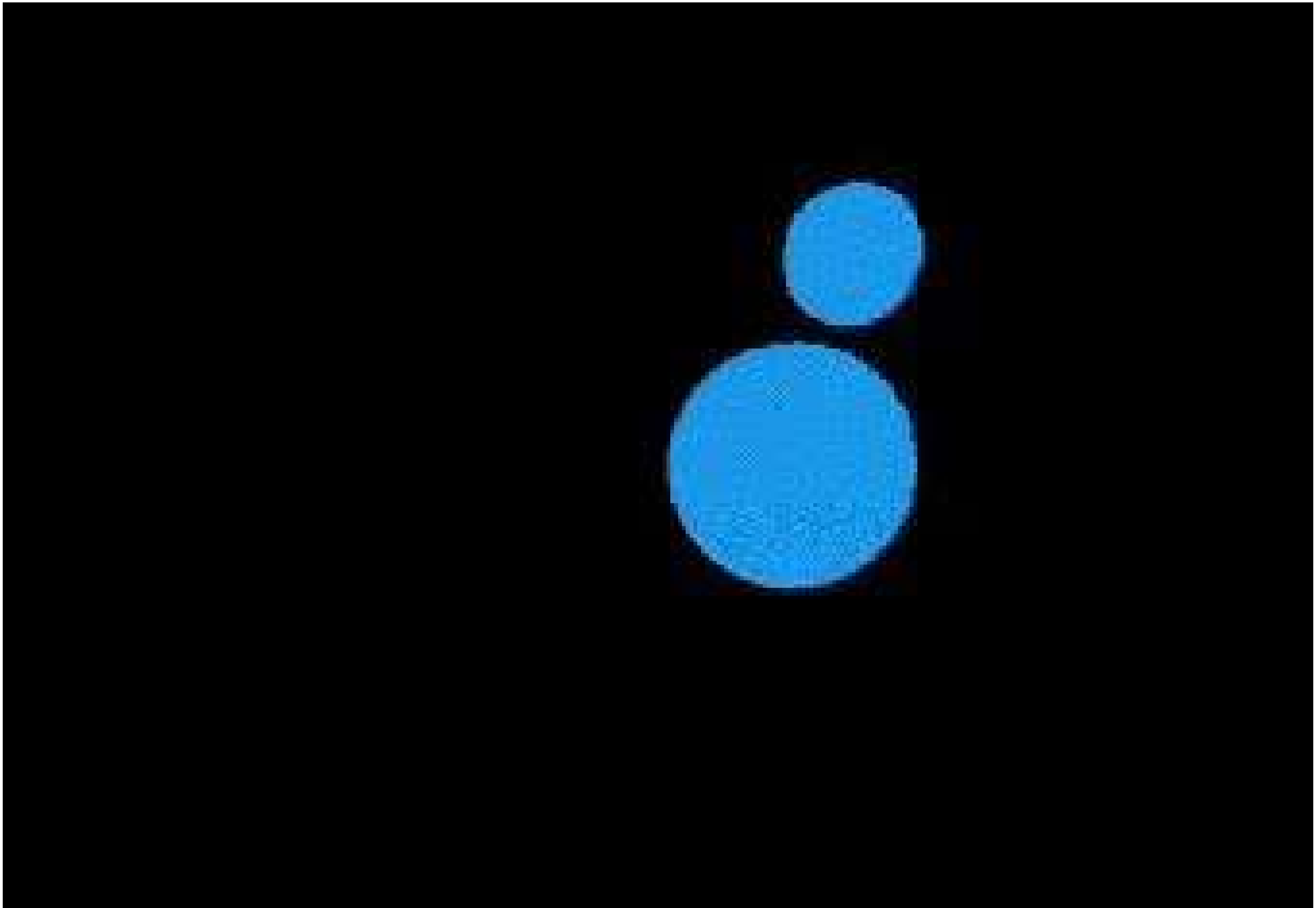
Modeling giant impacts: Approach

- Computer models
- Planets described by thousands to millions of particles
- Good for treating physical deformation, spatial dispersion of material, & thermodynamic response (heating, pressure, melting/vaporization)



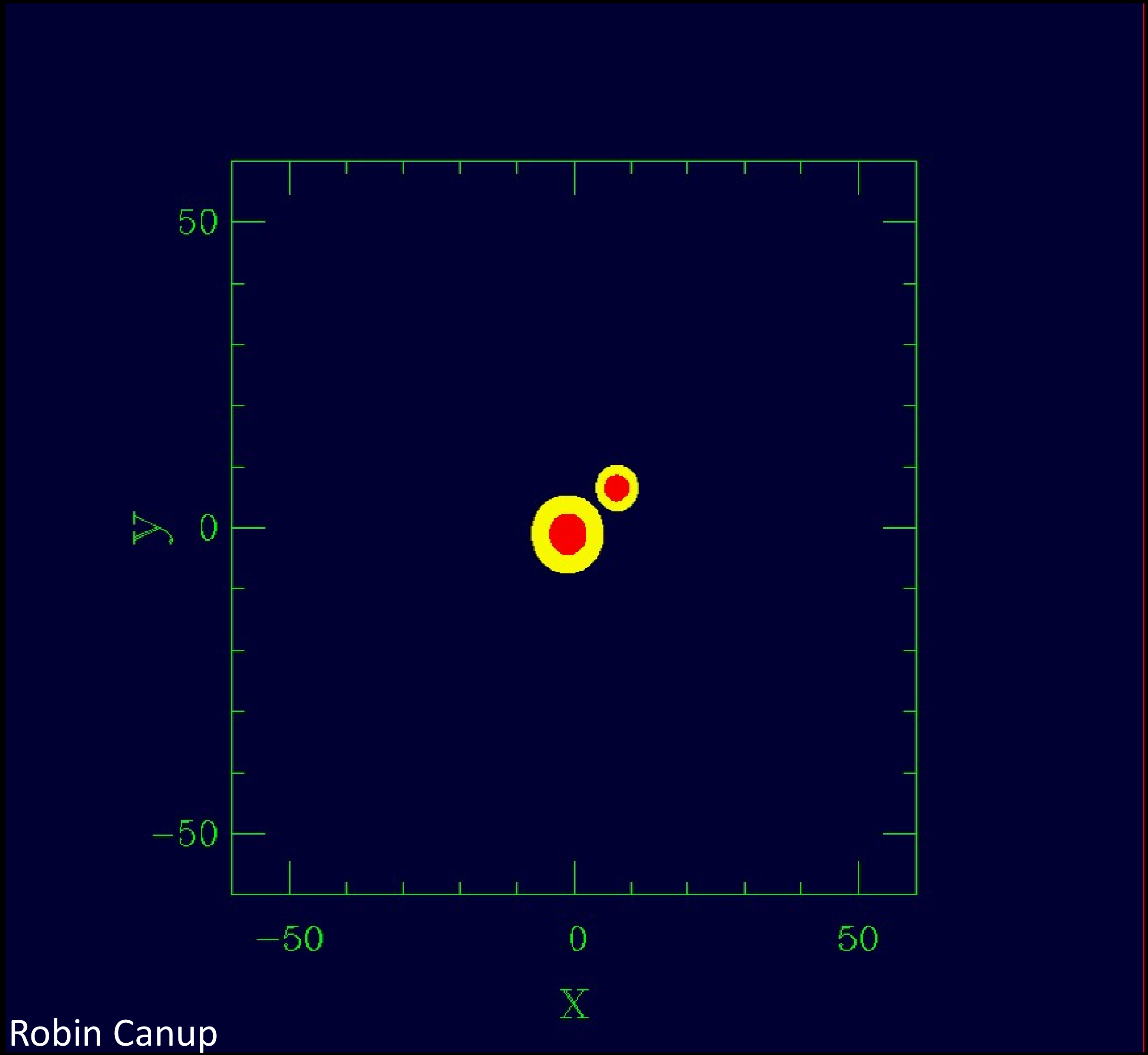


Animation by Robin Canup



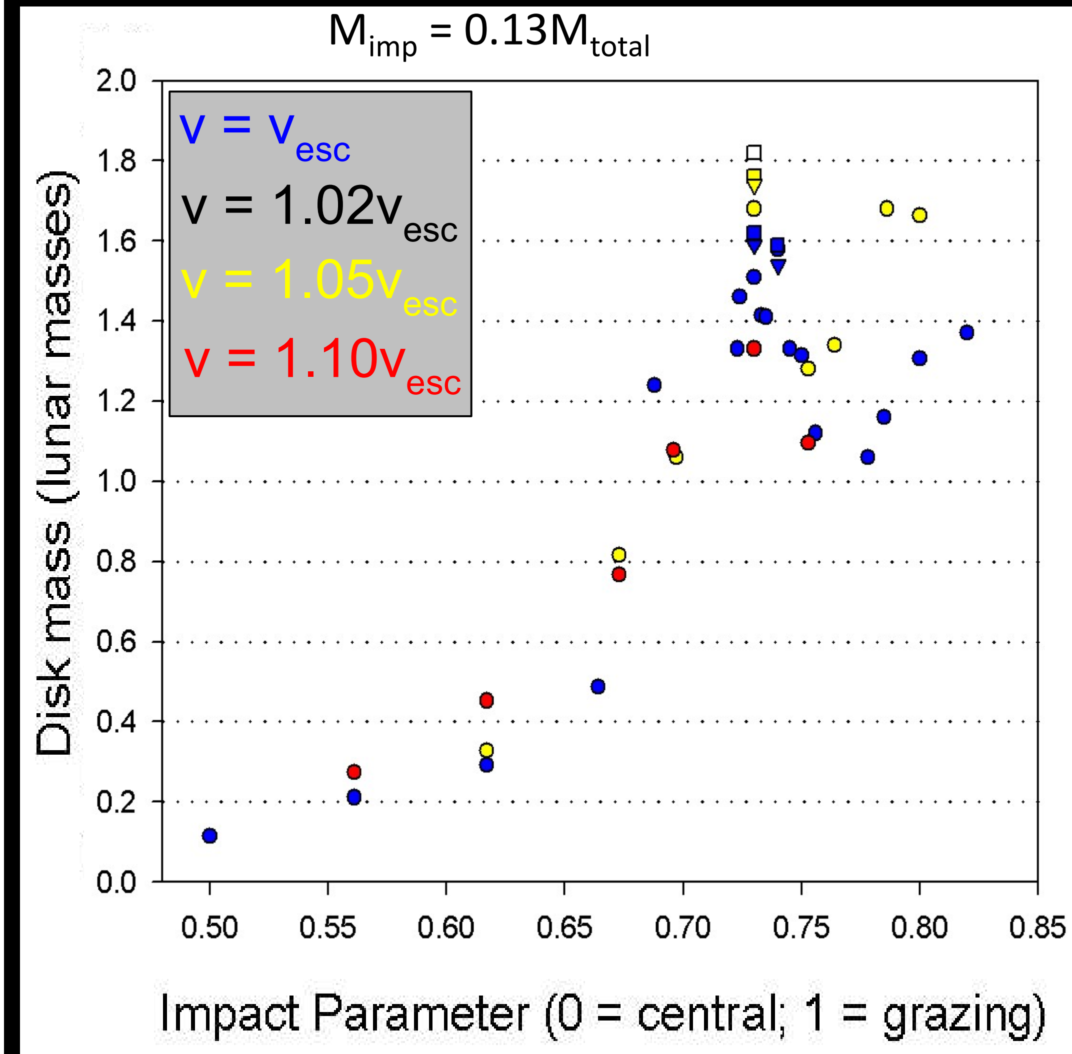
Animation by Robin Canup

Iron core vs. silicate mantle

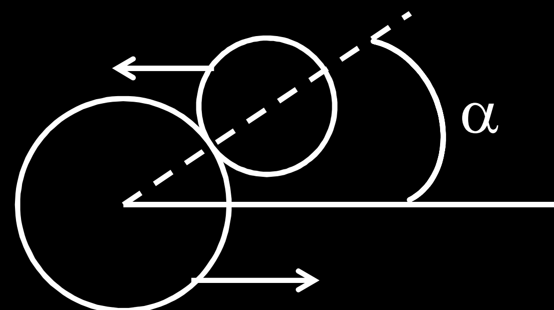


Animation by Robin Canup

General trends in impact outcome



- Impact parameter b=sin(α)

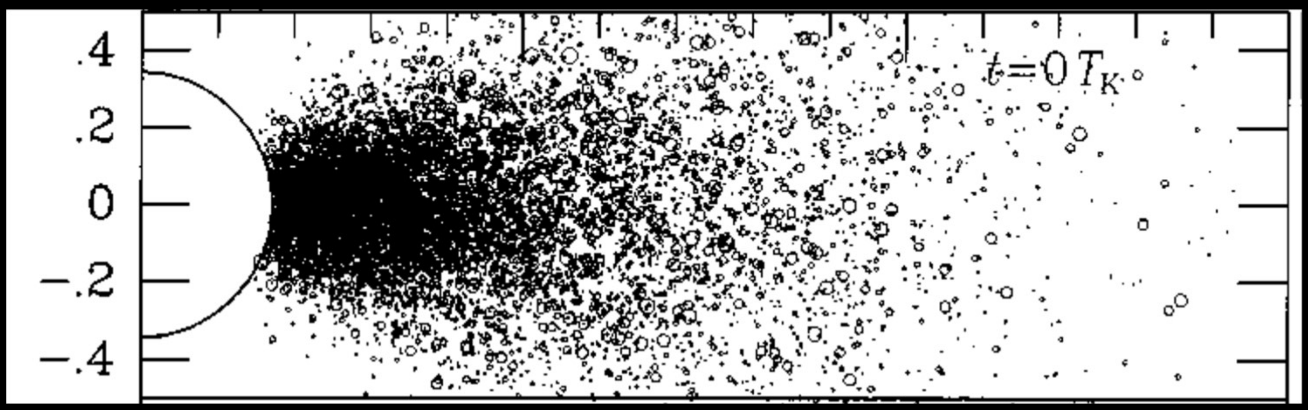


- Oblique b> 0.7 impacts yield orbiting material

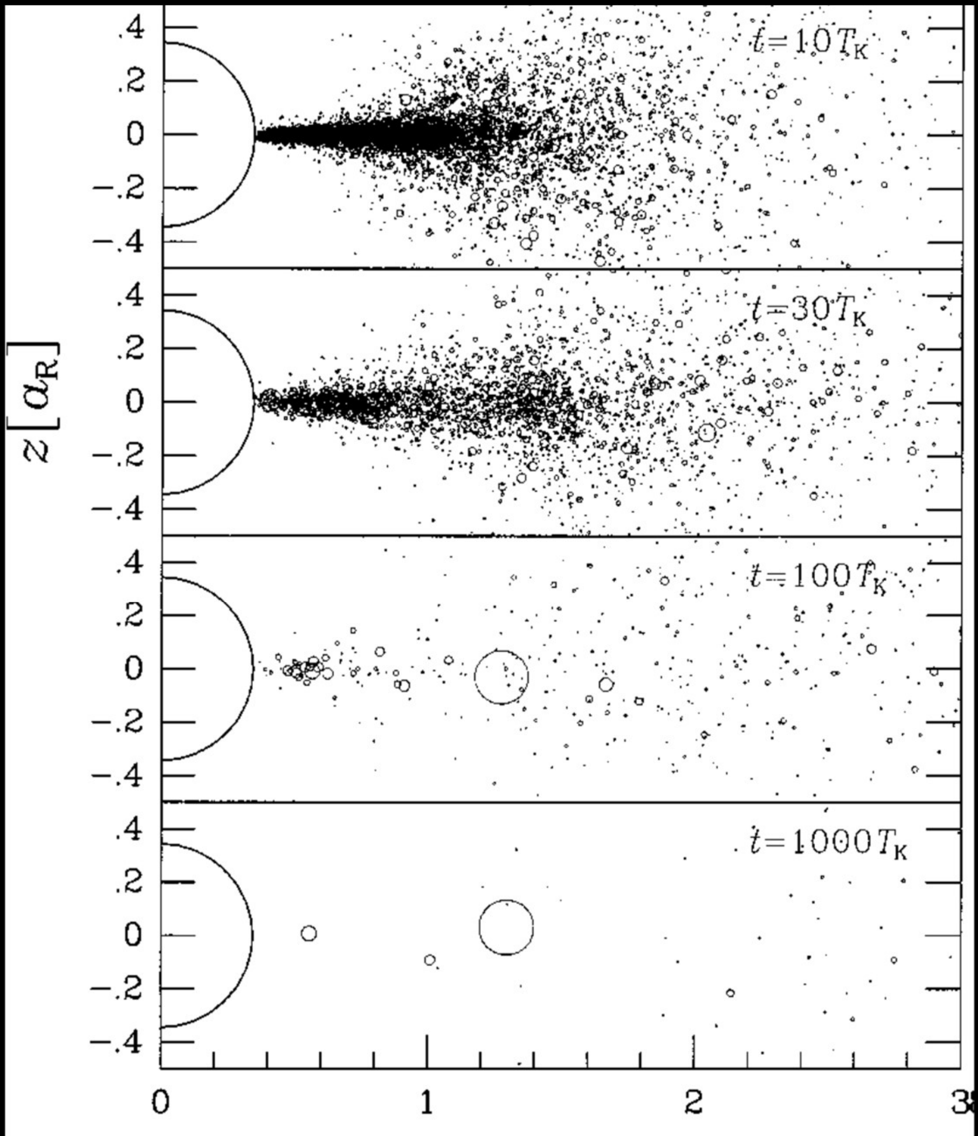
From a disk to a Moon

- How do particles in the disk end up forming the Moon?

- Computer simulations of the protolunar disk
- Protolunar disk represented by a collection of $10^3 - 10^4$ particles



- Only gravitational interactions
- No thermodynamics, vapor, fragmentation



Kokubo et al. (2000)

Sample Lunar Accretion Simulation:

- N = 10,000 particles
- t = 1000T_K is about 10 months

- Initial disk mass = $4M_{Lunar}$
- Final Moon mass: $1.2M_{Lunar}$

Formation of a ~lunar-mass object in less than a year

Summary of lunar forming impact models

1. "Successful" cases (Fe < 10%, $M_S \geq M_L$, $L_F \sim L_{EM}$):
   - Impactor $\sim$10 to 20% of Earth's mass
   - "Oblique" impact, with angle $\sim$35 to 50 degrees

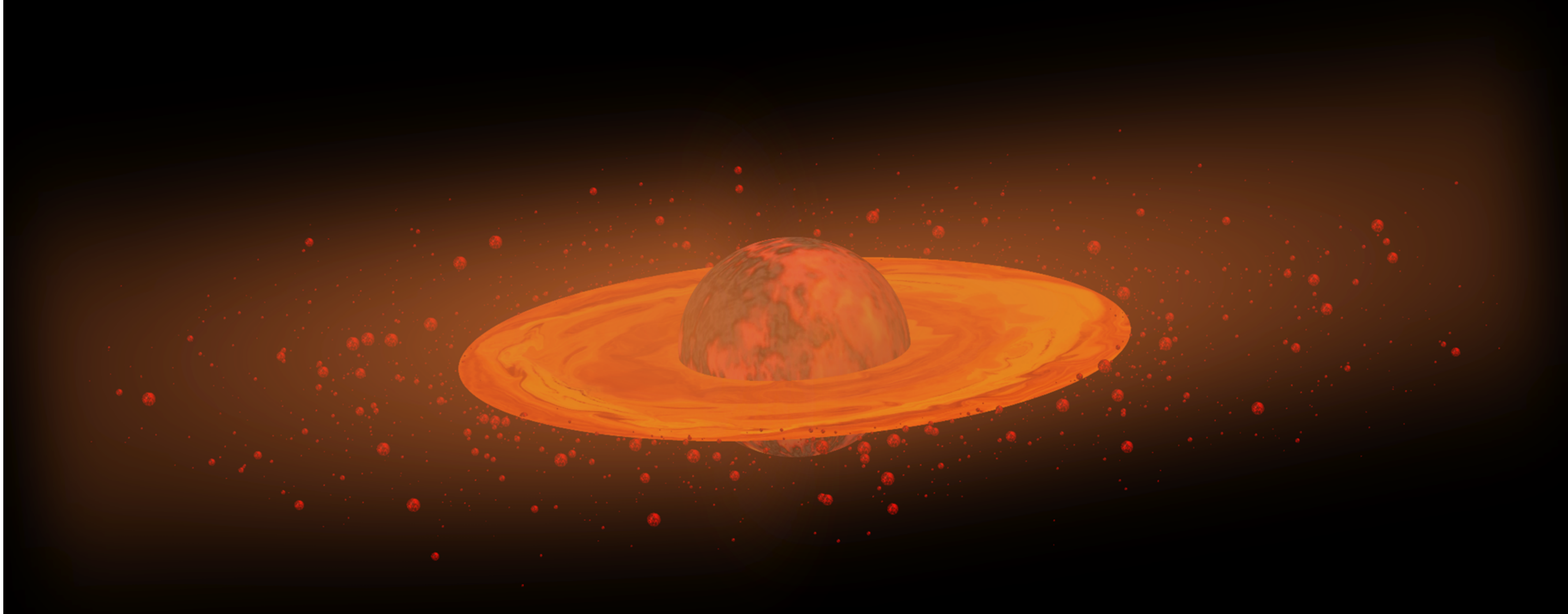
2. Orbiting mass derived from impactor (> 60%)

But Earth & Moon have nearly identical composition of multiple chemical elements

$\rightarrow$ *Impactor had same composition as target?*

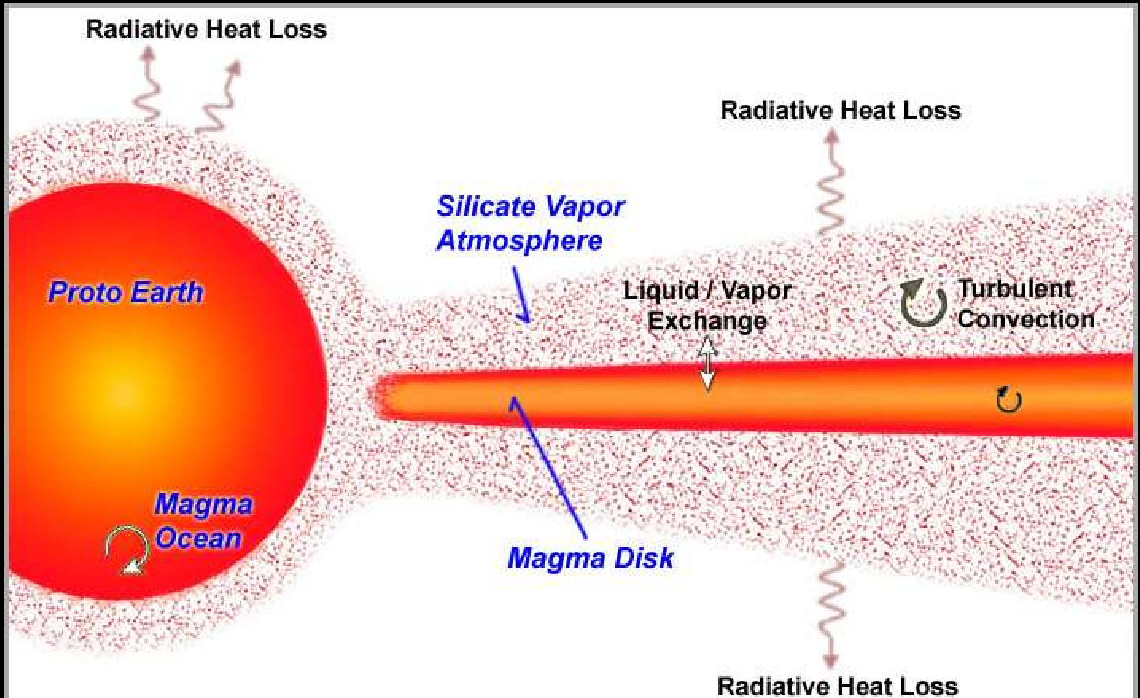
$\rightarrow$ *If not, need another mechanism*

The Earth-Moon System circa *4,5 Ga*



Protolunar disk is a very hot mixture of vapor and magma

Equilibration



(PSRD graphic based on Pahlevan and Stevenson, 2007, *EPSL*, v. 262, p.438-449, Fig. 3.)

- Material exchange between Earth and disk's atmospheres
- Compositional equilibration in ~100-1000 years (Pahlevan & Stevenson 2007)
- N-body models predict accretion timescale < 1 year…

Modeling the protolunar disk

- Roche limit: distance beyond which bounding forces between 2 objects overcome disruptive tides from the planet

  $\Rightarrow$ Objects of a given material can only merge if they are far enough from the planet

- Within Roche limit: gravitational instabilities form clumps that are then destroyed by tides = high collision rate

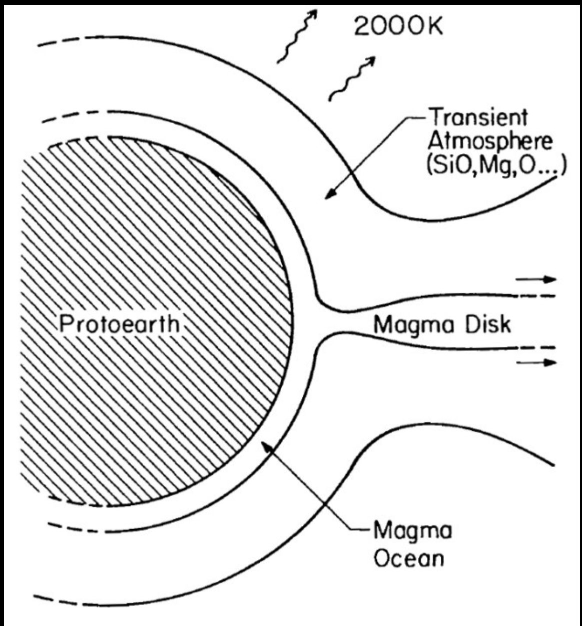
  $\Rightarrow$ particle disk would rapidly vaporize

  $\neq$ condensed particles

  $\Rightarrow$ Disk inside Roche limit should be represented by a fluid

- Outside Roche limit: disk rapidly fragments

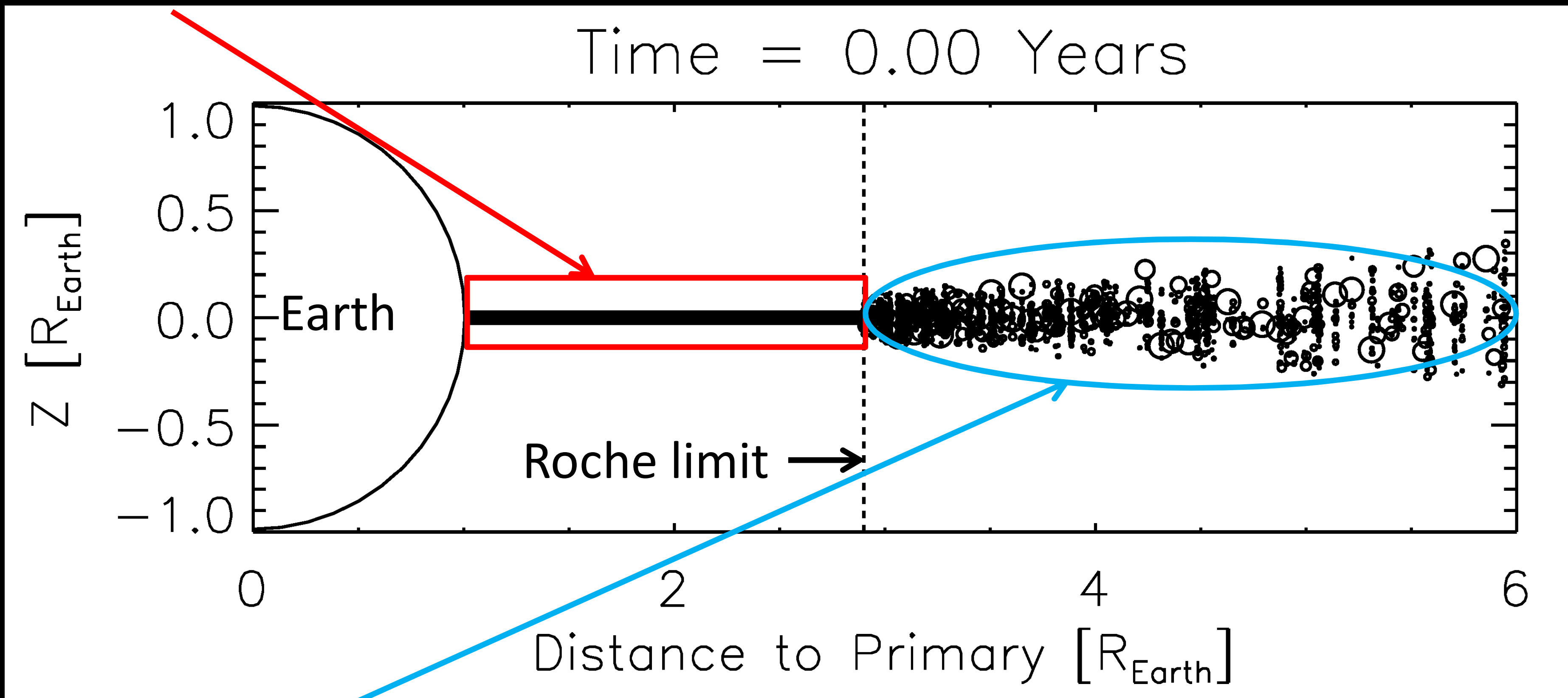
  $\Rightarrow$ Particle model is more appropriate



From Stevenson (1987)

Hybrid disk model

within Roche limit: uniform fluid disk



beyond Roche limit : individual particles

Viscous spreading

- Physical & thermodynamical processes in the disk transport angular momentum from inner to outer regions

- The rate of transport can be modeled by a *viscosity*
- Conservation of the angular momentum of the disk causes it to "spread" outward

- This process can bring material beyond the Roche limit, where new *moonlets* can form

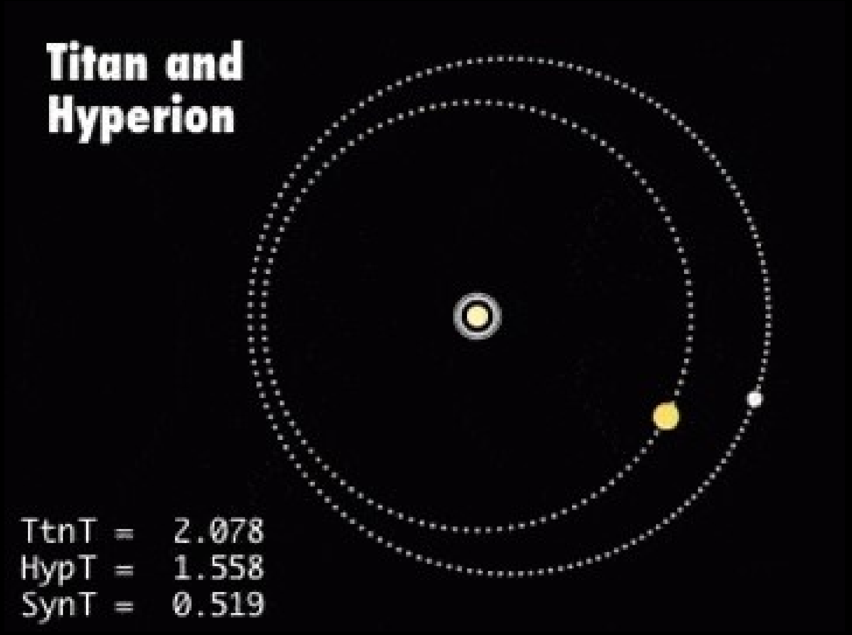
Resonances

- The orbital period increases with distance

- For a given satellite position, there are positions inside its orbit where a particle would do exactly *N* orbits while the satellite

  does *P* orbits

  $\Rightarrow$ *Resonances*

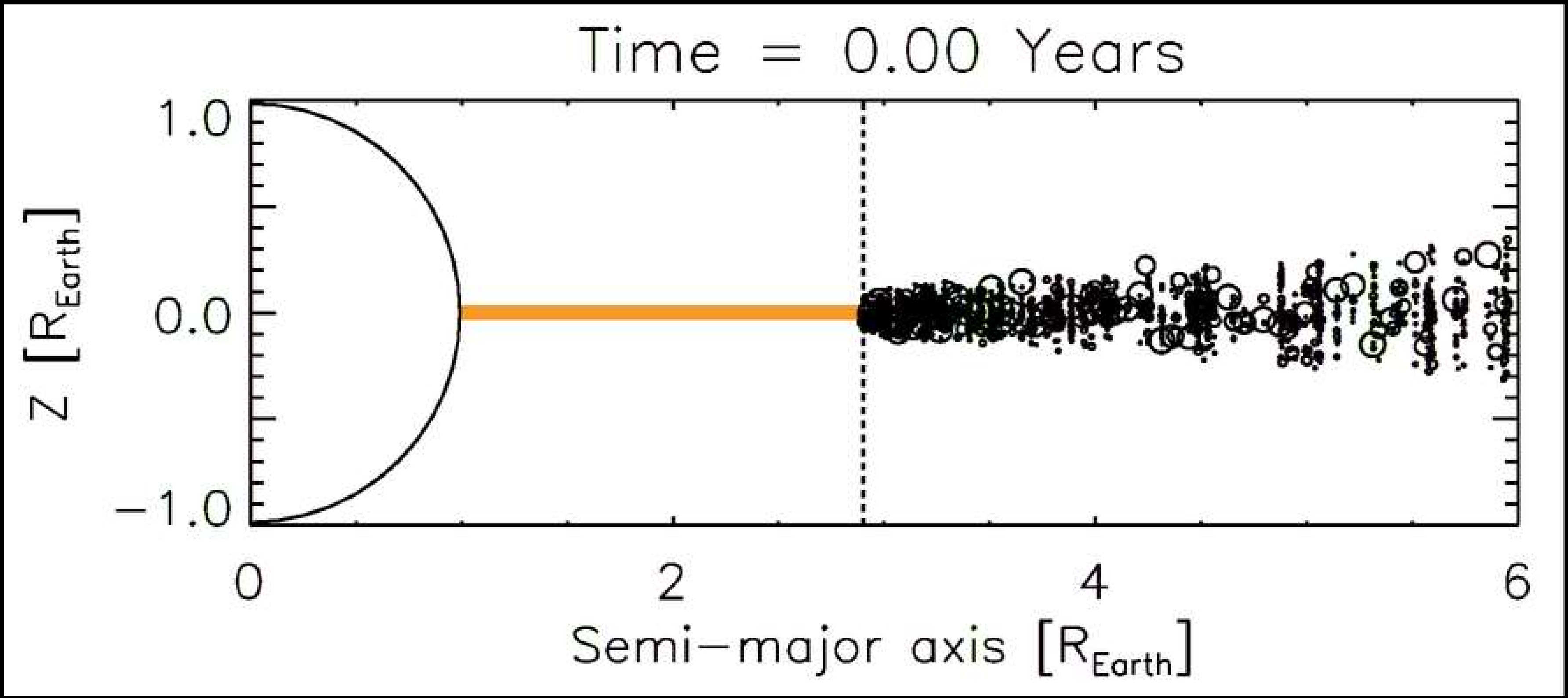


- For a disk and a satellite

  $\Rightarrow$Viscous spreading transfers ang. mom. from disk to satellite

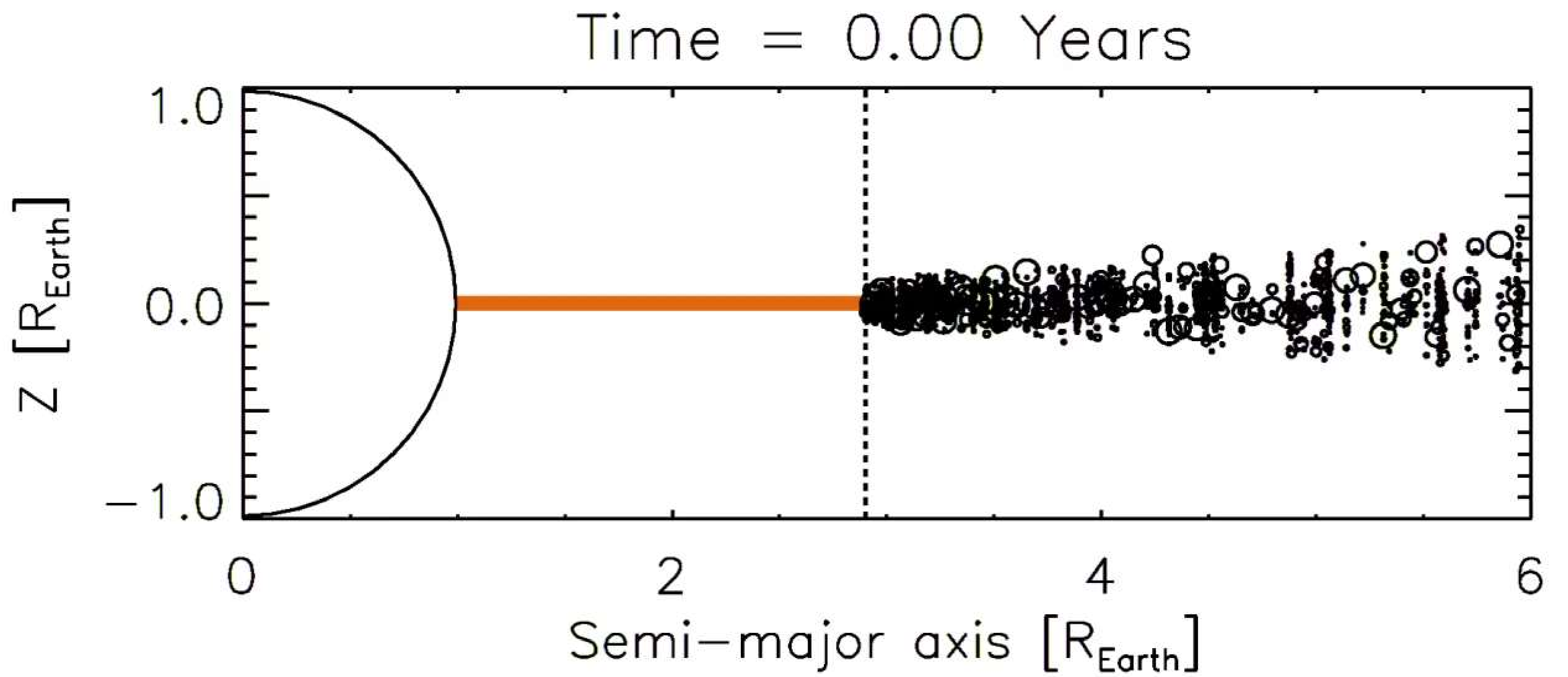
  $\Rightarrow$The disk contracts & the satellite moves away

A typical simulation

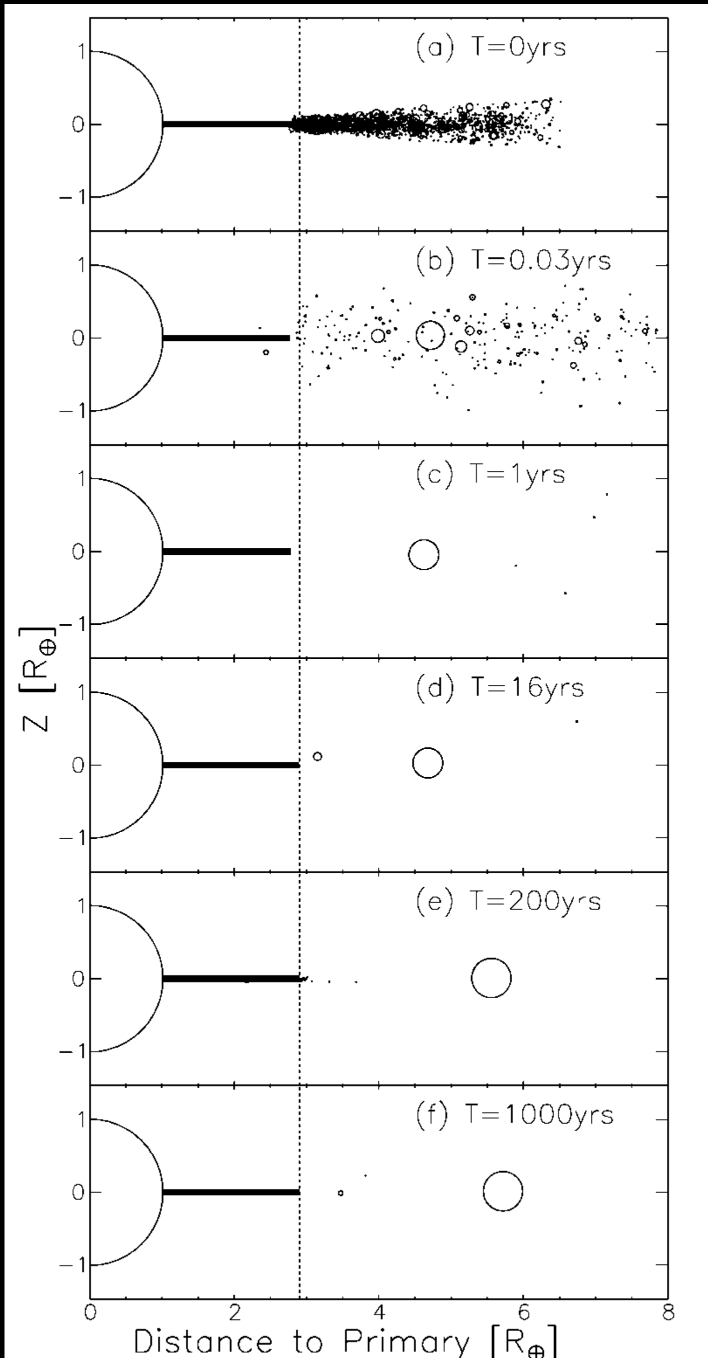


- Mass inner disk: 2 M_L
- Mass outer disk: 0.5 M_L
- Outer edge: 6 $R_\oplus$

A typical simulation

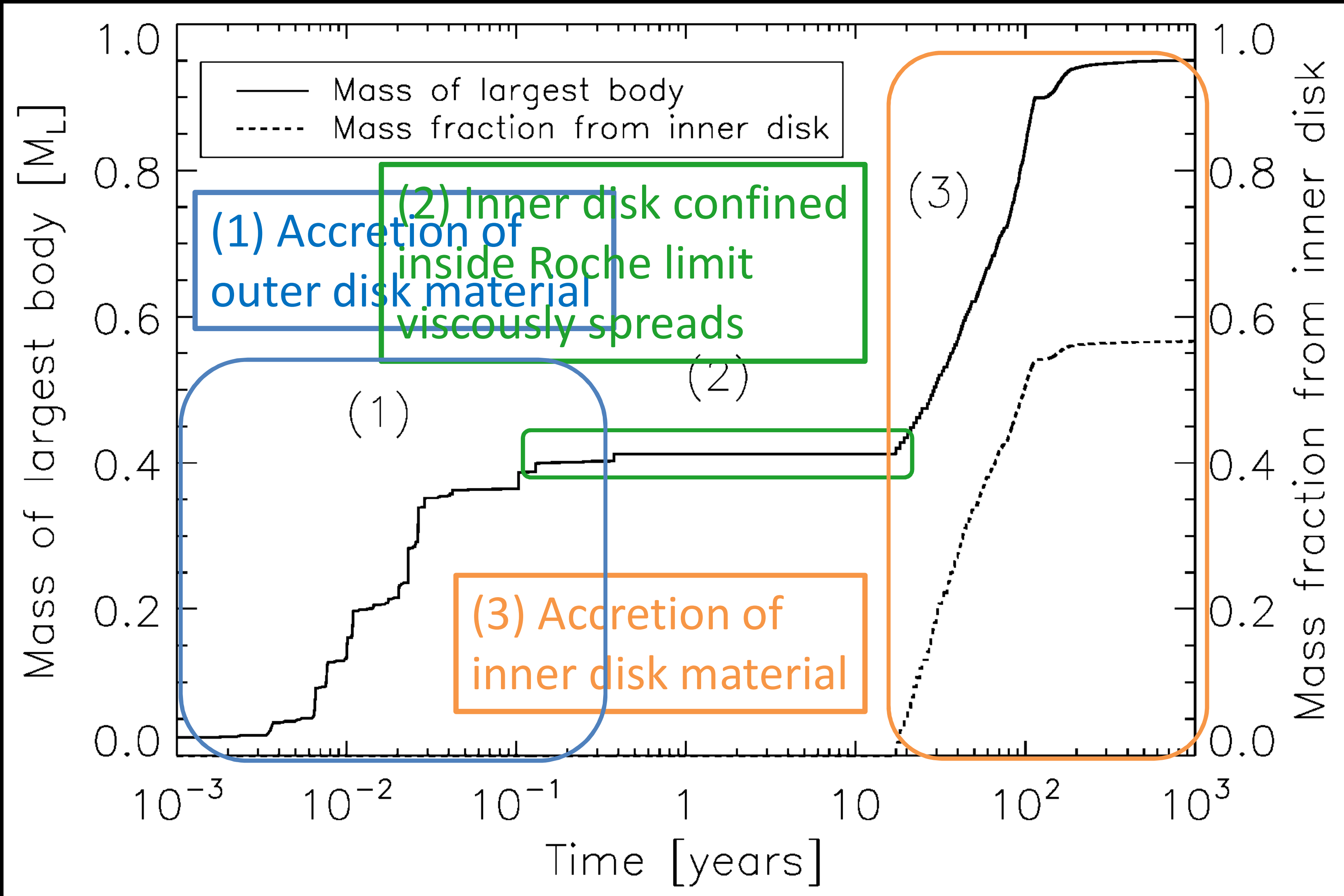


- Phase 1: outer bodies accrete and confine inner disk inside Roche limit
- Phase 2: inner disk slowly viscously spreads back out
- Phase 3: new bodies accrete at Roche limit and continue growth of the moon + serve as relay with inner disk causing moon orbit to expand

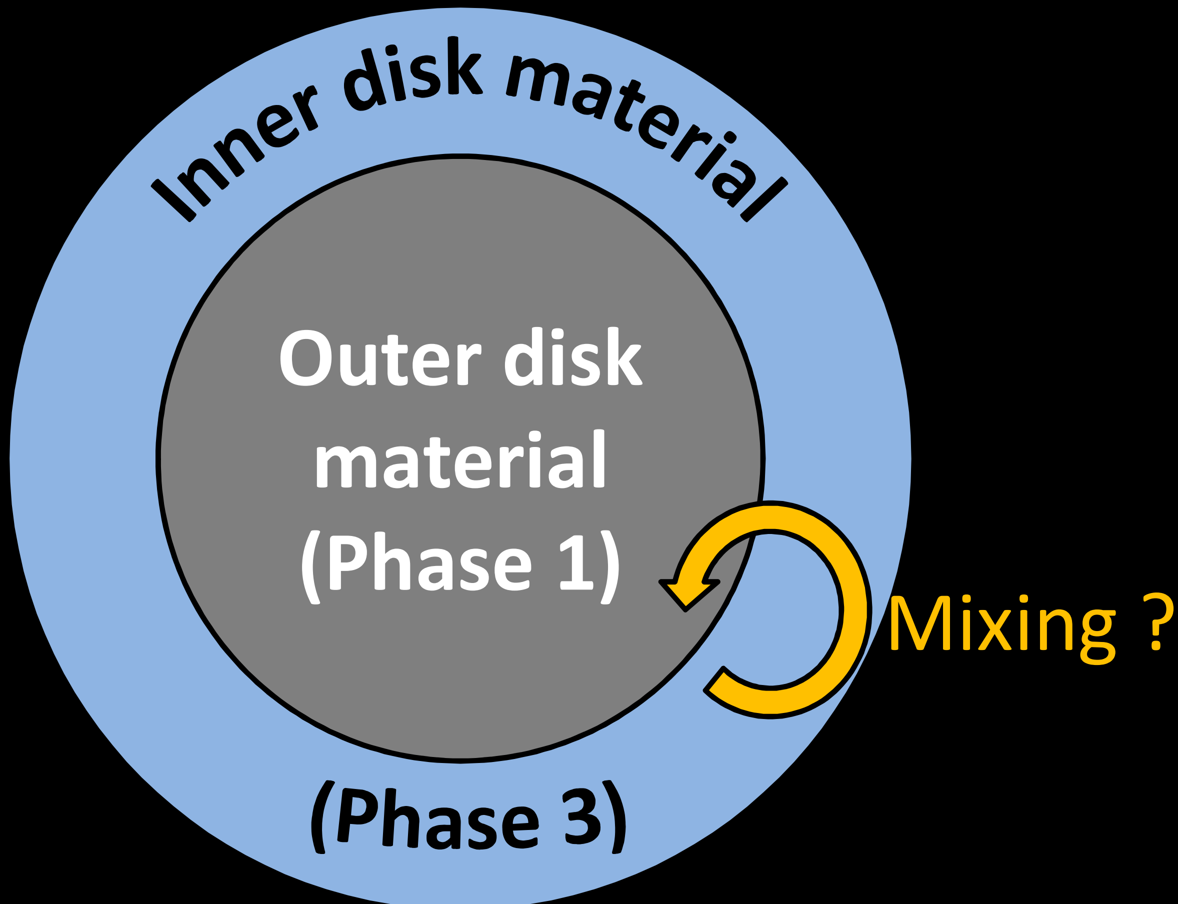


- All material in the outer disk is accreted in < 1 year
  $\Rightarrow$ same as N-body simulations
- Inner disk confined inside Roche limit by outer bodies
- Low radiation-limited viscosity
  $\Rightarrow$ disk spreads back to Roche limit in O(10) years
- Accretion lasts for $O(10^2)$ years
- Moonlets accreted at Roche limit serve as angular momentum relay that drive the Moon > 6 $R_\oplus$

A long 3-step accretion



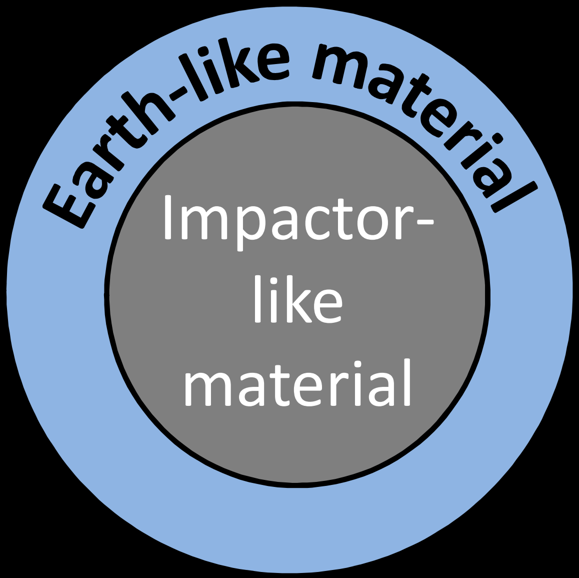
Resulting Moon structure ?



Implications

- Accretion timescales ~ 200 years

  ⇒ compatible with estimated equilibration timescales
- 3-steps accretion:
  - Moon "core" accretes fast in outer disk, no equilibration
  - Potentially equilibrated "Earth-like" material accreted last
- Earth-like material preserved on top of Moon if not fully mixed? → e.g. cold interior suggested by GRAIL results (Andrews-Hanna et al. 2012)



Summary

- A late Giant Impact on the Earth can form an iron-poor disk from which the Moon accreted
- Compositional similarities between the Earth and Moon can be explained if
  - Impactor identical to Earth
  - Impactor different, but disk composition evolve by mixing with the Earth's atmosphere
- The Moon forms over ~100 years and at ~$6R_E$


Questions?
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